NTNU – Trondheim
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Utilization and estimation of waste heat in buildings by using heat pump

Ranka Gojkovic

Master's Thesis
Submission date: April 2014
Supervisor: Natasa Nord, EPT

Norwegian University of Science and Technology
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MASTER THESIS

for

Ranka Gojkovic

Autumn 2013

Utilization and estimation of waste heat in buildings by using heat pump

Utnyttelse og evaluering av spillvarme i bygninger ved bruk av varmepumpe

Background and objective

In modern buildings, there is a simultaneous need for heating and cooling. For example, heating of IT rooms is necessary the entire year. Condenser heat from cooling plants can be used for various purposes in the buildings. At the same time, the modern building can be connected to the district heating network. This means that a building can provide its heating demand by utilizing district heating and condenser heat. However, coincidence and amount of these two heat flows are different. This can be challenging in operation of the modern buildings. Therefore, it is important to optimize the energy flows in buildings and utilization of the excess heat. Student will analyze the potential that lies in condenser heat and propose measures to make better use of waste heat in the modern building. To optimize energy flows and analyze the potential in the condenser heat, student will develop models of buildings installations. Models can be based on both thermodynamic principles and practical assumptions. A typical installation with a cooling plant for IT producing at the same time cooling and rejecting heating to support building heating can be analyzed. Student can use both Excel and MATLAB for the analysis. The aim of the study is

This master thesis has aim to define the possibilities for utilization of the condenser heat in building by analyzing a cooling plant that provides at the same time heating and cooling to the building.

This assignment is realised as a part of the collaborative project "Sustainable Energy and Environment in Western Balkans" that aims to develop and establish five new internationally recognized MSc study programs for the field of "Sustainable Energy and Environment", one at each of the five collaborating universities in three different WB countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2013.

The following tasks are to be considered:

1. Literature review on heat pumps, consumer substations, and waste heat in modern buildings. Student should learn about different performance estimation methods.

2. Define a case building with belonging heating and cooling loads. For the beginning, the candidate can start with some typical profiles for heating and cooling.
3. Develop estimation method to estimate waste heat and part of the waste heat that can be utilized in the building. Perform parametric analysis of the developed models for estimation of the waste heat.
4. Present and discuss the results.

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When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analysed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 16. September 2013

Olav Bolland
Department Head

Natasa Nord
Academic Supervisor

Research Advisors: Prof. Vojislav Novakovic
Dušan Golubović, University of East Sarajevo

Preface

This report represents my Master Thesis, conducted during the last semester at the MSc study Sustainable Energy and Environment, class of 2012. This thesis has been written at the Department of Energy and Process Engineering, Norwegian University of Science and Technology, NTNU, in Trondheim, Norway, autumn 2013.

Abstract

This assignment is realised as a part of the collaborative project “Sustainable Energy and Environment in Western Balkans” that aims to develop and establish five new internationally recognized MSc study programs for the field of “Sustainable Energy and Environment”, one at each of the five collaborating universities in three different WB countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2013.

In this paper, a low-energy office building in Norway has been analyzed. The case building is located in Trondheim at the address Professor Brochs gate 2, as shown in Figure 1. The building is rented as an office building to nineteen different companies.

This master thesis aims to define the possibilities for use of the condenser heat in building by analyzing a cooling plant which provides both heating and cooling to the building at the same time.

The paper explains the optimization of the heat pump, responsible for the cooling of rooms in the building. The optimization is used for defining the parameter values which give the greatest energy saving and, besides that, their mutual influence has been shown in the optimization process, as well as the influence of the parameters to the energy saving.

Table of contents

List of symbols

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Symbol	**Signification**	**units**
Pcomp (W)	Power used by the compressors in the heat pump	kWh
Qcond	Condenser load	kWh
Qev	Cooling load given by the evaporator to the cooling circuit	kWh
Tsup	Average supply temperature in the main heating branch	°C
Tret	Average return temperature in the main heating branch	°C
Tout	Average outdoor temperature	°C
Tcond	Average of supply fluid temperature of the condenser	°C
Pcond_max	Maximum condenser pressure 40 bars	bars
Tcond_max	Maximum condenser temperature 62,49 °C	°C
Tev	Temperature in the evaporator (heat pump)	°C
ΔT1	Temperature difference beetwen Tsup and Tret	°C
ΔT2	Temperature difference beetwen Tcond and Tsup	°C
ΔT_{SC}	Overheated temperature in the heat pump	2°C
ΔT_{SH}	Overcooled temperature in the heat pump	2°C
COP	Coefficient of Performance	**-**
S	Energy saving	NOK, KM
C_{EL}	Electricity price	NOK/kWh
C_{DH}	District heating price	NOK/kWh

List of Figures and Tables

1. INTRODUCTION

In recent years, there is a lot of talk about the need of deceasing the energy consumption, and the problem which troubles politicians, experts and users is how to satisfy the need, especially after the world energy crisis, at the beginning of seventh decade of the previous century.

Heat pump has a significant role in transfer to renewable energy sources, providing a more efficient utilization of renewable energy sources, as well as of waste heat.

Heat pumps are not unknown in the system for saving and use of renewable energy sources. The history of their application and acquired experience show that they are a very good technical solution. Then, why do they not have a wider application? Maybe due to the fact that permanent changes in prices of energy and equipment change the direction of the heat pump application economy.

Heat pumps are used where renewable energy or waste heat can be used as a heat source to obtain useful thermal energy at higher temperature level.

The second important aim is the maximal use of waste heat.

In modern buildings, there is a need for both cooling and heating at the same time. For example, the cooling of IT rooms is necessary during the entire year. The heat from the condensers of cooling plants can be used for different purposes in a building. At the same time, a modern building can be connected to the distant heating network, and it means that it can provide its object the heating needs by use of distant heating and heat condenser.

However, the energy flow of distant heating and heat condenser is different. It can be a challenge for the use of a modern building. It is important to optimize the energy flow in buildings by using the excess heat.

This master paper aims to define the possibilities of using a heat condenser in a building through the analysis of the cooling plants which provide both cooling and heating in the building at the same time.

An installation with cooling plant for the cooling of IT room has been analysed, which uses the waste heat and thus supports the heating of the building.

The paper also performs the analysis of the potential lying in the heat condenser, and the heat pump operation optimization with the aim to improve the system and decrease the energy consumption in the building.

After a brief general analysis of the building, the paper gives a detailed analysis of the cooling plant, explaining the role and operation of each component.

Due to the fact that the goal of the study is the system optimization using mathematical models, the results obtained by calculation have been presented by means of diagrams, and after tht, by changing of some parameters and the hypothesis, the heat pump optimization has been performed.

2. CASE STUDY

2.1. Building specification

The analysed building was built in 2009, under the name “the construction of the year”, it presents a project worth 215 million NOK. It is in Trondheim, at the address Professor Brochs gate 2, as it is shown in Figure 1.

Figure 1: Location of the analysed building in Trondheim

The building is marked with a yellow sign and number 1 and it is places along the main road marked with red colour, Figure 1. It is being rented as an office building for 19 different companies.

The paper presents the results for the named building, which is presented in Figure 2. He object height is 21 m (front block) and 14 m (rear block). The building has 6 floors and a basement. It mostly consists of offices, meeting halls and common rooms. The building has 16 200 m^2 of heating area and it is in Trondheim, where the outdoor design temperature is –19 °C, and the average outdoor temperature is 6 °C. Since September 2009, the building has been used as a office building.

Figure 2: Office building in Trondheim

The building has been built in accordance with a low energy standard. The low energy for the windows. Besides that, the standard implies the infiltration of 0.1 air changes per hour.

A building is first considered to be energy efficient when it consumes less energy per square meter than the average building within a geographical area. Older buildings annually consume an average of about 160 kilowatt-hours per square meter [kWh/m^2] while low energy buildings annually consume an average of 40, and passive buildings an average of 15 kilowatt- hours per square meter [kWh/m^2]. Additionally, buildings with direct electricity as the primary heating source are regulated with even stricter energy consumption requirements.

Many improvements have been made at this building during its construction with the aim to decrease the energy consumption. The example for that is shown in Table 1.[1]

Table 1: Improvements about the energy needs of the building

Average energy needs for modern office buildings	288 kWh/m^2/year
Building energy need regulation Tek 07	165 kWh/m^2/year
Energy need required by the concract (Enova)	150 kWh/m^2/year
Calculated actual energy needs	83 kWh/m^2/year

Energy needs required by the contract were 150KWh/m^2 per year, however, due to the performed measures the “Calculated actual energy needs“ have been achieved, what is almost one half of the needed (83 KWh/ m^2).

2.2. Description of the building substation

The building substation has been designed as it is shown in Figure 3. The building is supplied with heat by two energy sources: distant heating (the main part) and a heat pump. The other heat pump is used for cooling the IT rooms.

Section 1: A heat pump (35.01) is used both for heating and cooling of rooms in the entire building. It consists of 6 chambers distributed in three configurations, evaporator, condenser and return valve. Due to the fact that this system is reversible, the evaporator can become the condenser and vice versa.

Section 2: The heat pump (35.02) which cools the plant is the subject of this study, the description will be performed in the next chapter. It is used for cooling the IT rooms.

Distant heating: It provides hot water for radiators, steam heating, snow melting, ventilation and hot sanitary water. To be more accurate, the connection between the primary and secondary side is indirect, by means of heat exchanger for distant heating system, the type of connection allows the low pressure in house installations to be retained, better control on the basis of demands and the decrease in leakage possibility, in spite of the increase in investment costs.

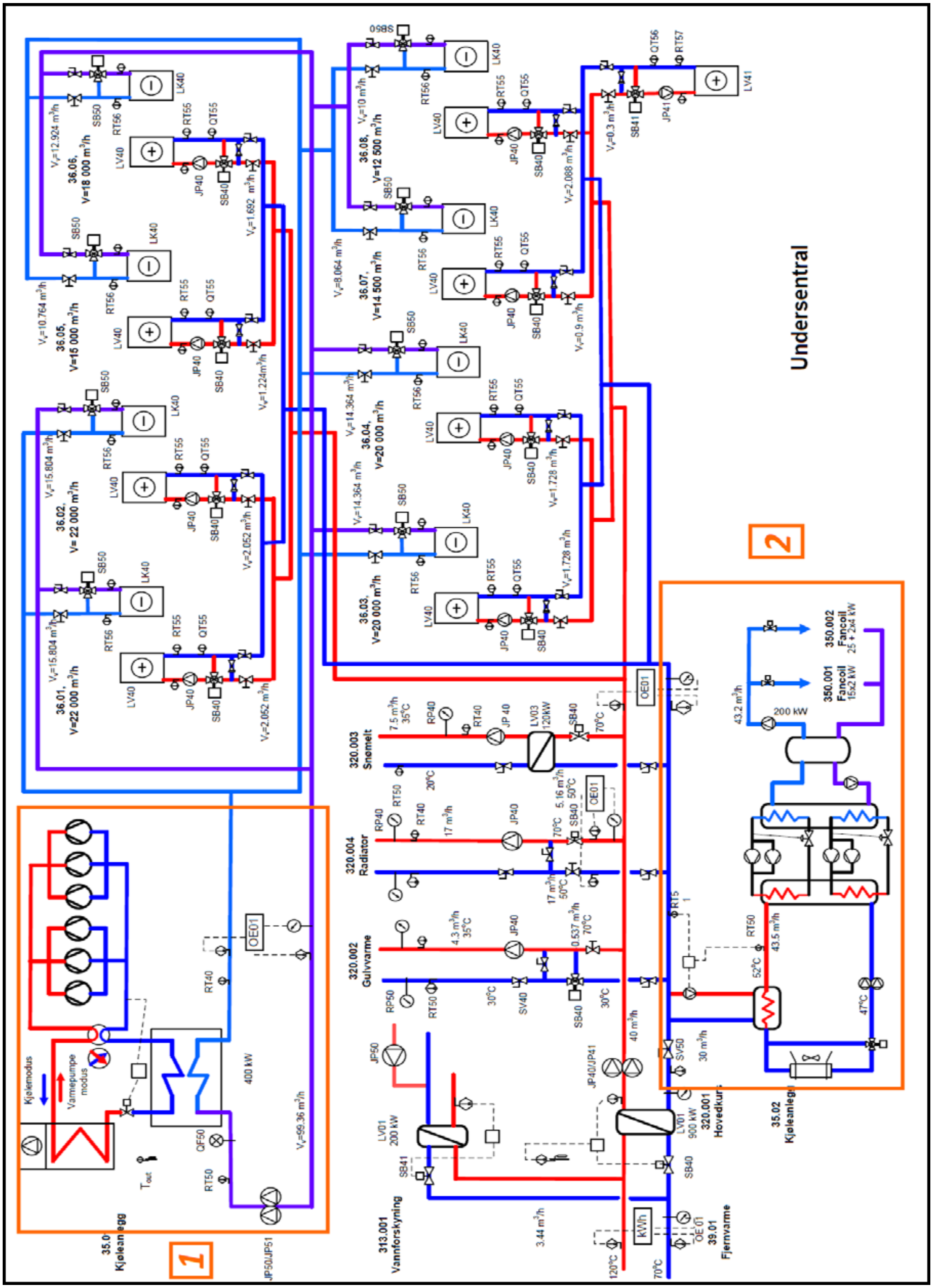


Figure 3: Scheme of the building substation

It can be seen from the Figure that the heating is provided by means of radiators and underfloor heating, while the cooling of IT room is provided by means of fan-coil device. The thermal energy for ventilation, room heating, snow melting and hot water is delivered by heat pumps and distant heating. The scheme of the entire substation in the building is shown in Figure 3. The two installed pumps, 35.01 and 35.02 in Figure 3 (section 2 and section 3), provide heating and cooling as it is explained in the text that follows. The heat pump 32.01 is a plant for cooling and it provides the cooling of IT room, while the heat condenser is used as a support for heating. In this way, the distant heating demand should be decreased. Distant heating is the main energy source for heating the building. The supply temperature and return temperature of distant heating supply are 120/70 °C at the side of the supplier. The building is provided with two heat exchangers for thermal energy reception. The heat exchanger of 900 kW, 320.001 is the installed device for construction, while the heat exchanger of 200 kW, 313.001 was installed for domestic tap waters.[7]

3. SYSTEM DESCRIPTION AND ANALYSIS

As it was mentioned before, the study is focused on the cooling plant, presented in Figure 3 (section 2). To perform a more detailed study on all the components, the system has been divided in three parts:

- Warm side of the heat pump
- Heat pump
- Cold side of the heat pump.

In that way, the operation of all the components and all three parts of the plant have been analysed.

3.1. Warm side of the heat pump

At first, we will describe the hot side of the heat pump connected with the main branch of the main heating system presented in Figure 4.

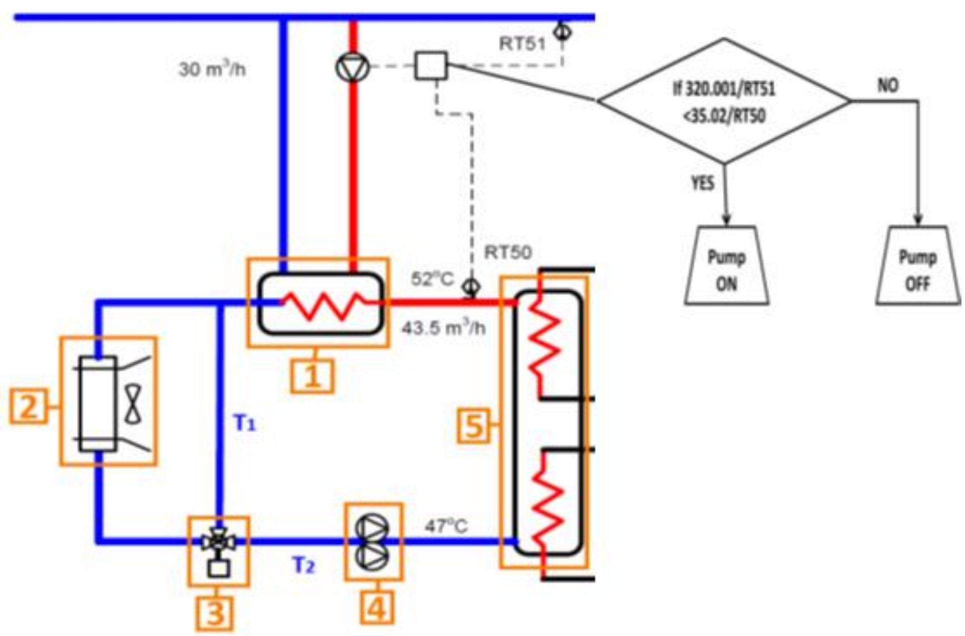


Figure 4: Scheme representing the hot side of the heat pump

Where the numbers present:

1- Heat exchanger

2- Air condenser

3- Three way valve

4- Two pumps in parallel

5- Condenser

Before presenting all the components, the condition of operation of heat exchanger (1) in the Figure 4 needs to be described. That is, there is a necessary condition for the circulation pump to run and thus to switch the heat exchanger on: the return water temperature (RT51) in the main heating branch, named as 320.001 in the Figure 3, needs to be lower than the leaving water temperature (RT50) of the cooling plant condenser (called 35.02 in Figure 3). That condition is shown in the flowchart in Figure 5. [1]

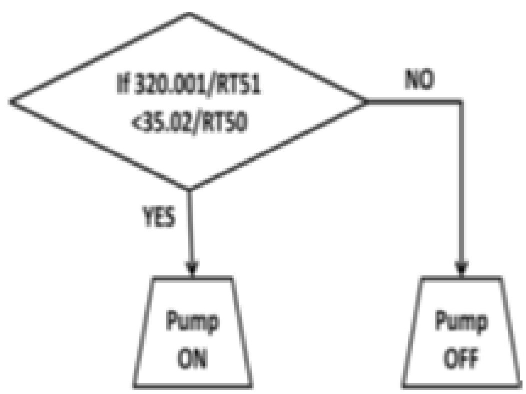


Figure 5: Flowchart of the heat exchanger operation

Therefore if this condition is fulfilled, the hydraulic pump will circulate the water in the heat exchanger and the warm side circuit will be cooled. Otherwise, the pump will remain turned off until the condition is fulfilled.

The aim of this heat exchanger is to cool the leaving water of the **condenser (5)** in Figure 4. This condenser works only if this return water from DH can cool the warm side,

thus this temperature (RT 51) needs to be lower. The return temperature of the main heating branch will also increase. As a result, the fluid in the main heating branch will need less energy to reach the same temperature of supplied water. Finally, this system allows the saving of the energy used by the utilization of the condenser load.
The air condenser (2) is used for cooling the water after the heat exchanger. The system is used as an addition to the heat exchanger and it cools the water if necessary. To save the energy, the use of heat exchanger in relation to the air condenser should be favoured, so that the heat still remains in the circle and does not go out. .

The three way valve (3) allows the mixing of water from the air condenser (2) and T1 to get the desired temperature T2 (Figure 4).

Two parallel pumps (4) are installed to circulate the water in the condenser (5), what allows the increase of flow without increasing the pressure in the system.

3.2. Heat pump

The basic goal of the heat pump is to transfer the amount of heat from the emitted side (IT room) to the receiver side (warm side) by means of the coolant. The heat pump uses R410A cooling fluid, which belongs to the group of HEC gases, it has a big compression and cooling capacities, and is also less harmful than the others (R22, for example). The ozone depletion potential (ODP) for this freon is equal to zero, while the global warming potential is 1725 [5].

Theoretical scheme of the heat pump operation is presented in Figure 6.

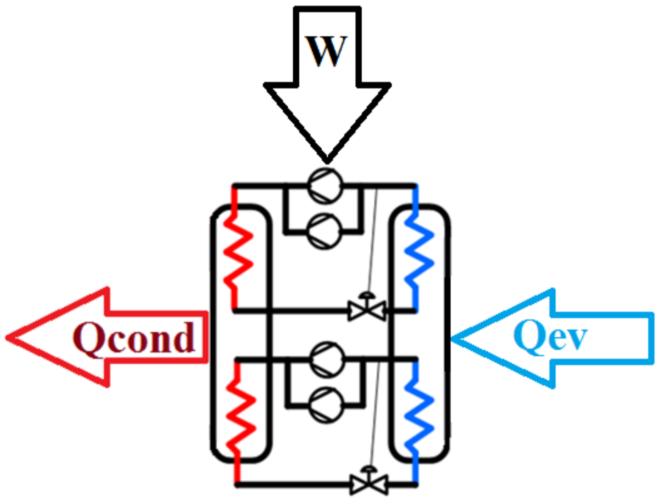


Figure 6: Scheme of the heat pump operation

In an ideal case, the formula which connects the power of compressor (Pcomp), condenser load (Qcond), and cooling load (Qev) is:

$$Pcomp + Qev = Qcond$$

As regards the efficiency of the heat pump, it is determined by the COP coefficient of performance

$$COP = \frac{Q}{W}$$

The analysed heat pump is presented in Figure 7.

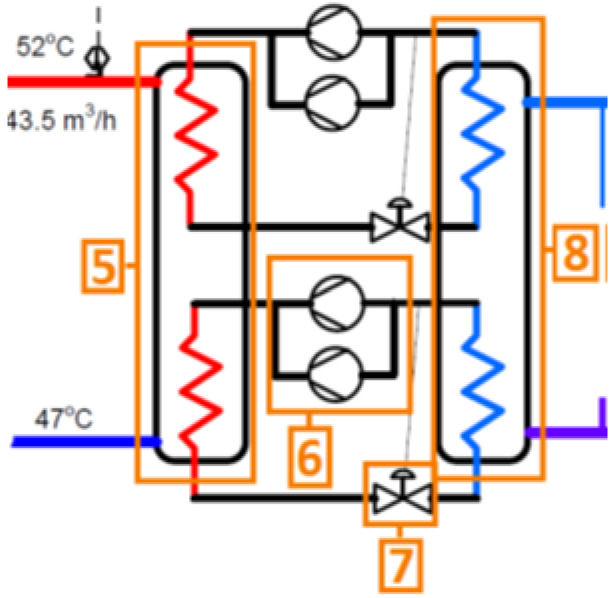


Figure 7: Scheme of the heat pump components

The heat pump consists of four parts

5- Condenser
6- Compressor distributed in duo configuration
7- Expansion valve
8- Evaporator

As it is seen in the figure, the heat pump has two different parallel circuits which improve the performance [6].

To explain the operation of the heat pump more precisely, we will use the Pressure/Enthalpy diagram shown in Figure 8, obtained by means of CoolPack software.

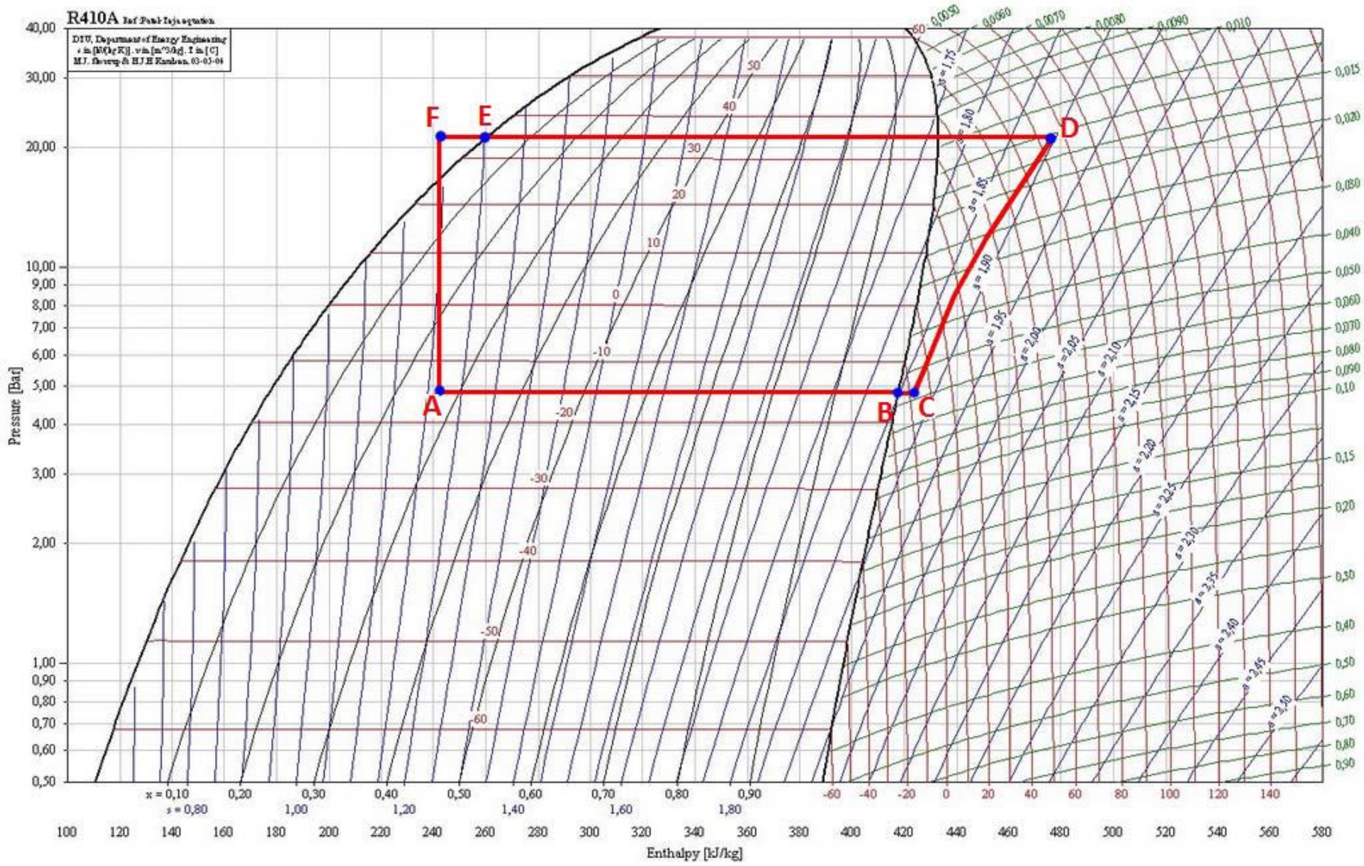


Figure 8: Cycle of the heat pump on a Pressure/Enthalpy diagram

With the help of this diagram it has been possible to explain the role of every component from Figure 7 for heat transfer from one side (cold side) to the other (warm side) and define the hypotheses which are used for further calculations. The Pressure/Enthalpy diagram has been obtained by using CoolPack.

- **Inside the evaporator (8)**

From A to B: the fluid evaporated, it gained heat through the evaporator with a constant pressure and temperature.

Hypothesis: we assumed that the evaporator temperature is Tev= 8°C [7].

From B to C: The gas was overheated to make sure that there was only gas which had gone into the compressor. Otherwise a liquid gets incompressible and thus the compressor might broke.

Hypothesis: After the evaporator, the gas was overheated (about 2 ° C) and with a low pressure.

- **In the compressor (6)**

From C to D: The gas was compressed in adiabatic way. Thus the pressure and the temperature were increased.

- **Inside the condenser (5)**

From D to E: The fluid released its energy through the condenser and passed in the liquid state.

From E to F: The fluid was overcooled to be sure there was only liquid and no more gas in the fluid.

Hypothesis:

- *The pressure of the fluid remained constant and the overcooled temperature was about 2°C.*

- *The pressure in the condenser cannot exceed 40 bars, which corresponds to the maximum condenser temperature of 62.49°C. [7]*

- **In the expansion valve (7)**

From F to A: The fluid was expanded through the expansion valve, it started to evaporate because of the pressure drop made by the valve.

Hypothesis: the enthalpy of the fluid remained constant.

3.3. Cold side of the heat pump (cooling of IT rooms)

At the cold side, the heat pump provides the cooling load for ventilator-convectors to cool the IT room. Figure 9 presents the circuit (ring road) of water between the evaporator and ventilator-convector.

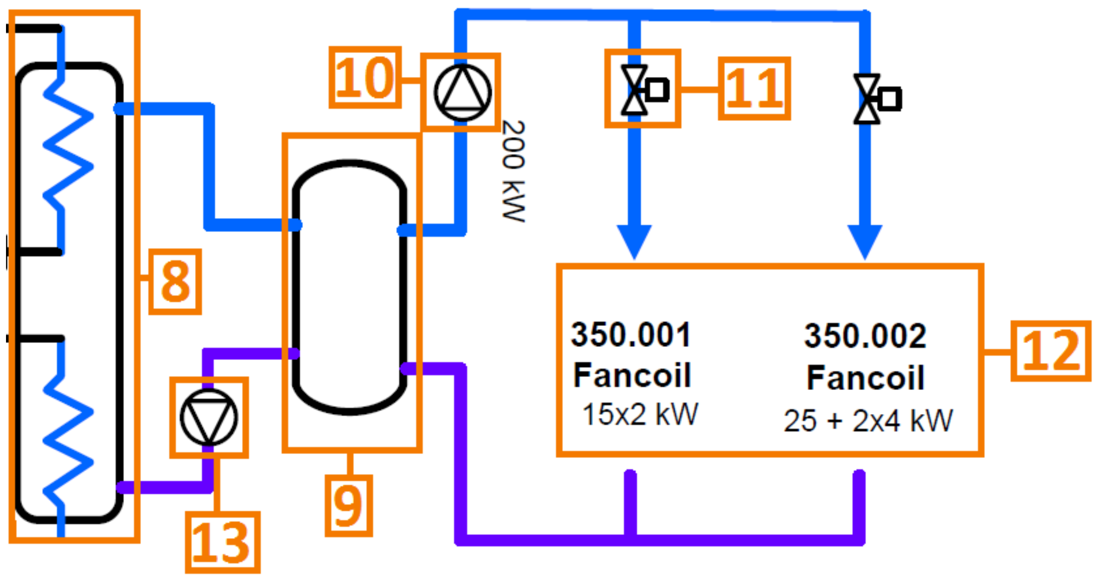


Figure 9: Scheme of the heat pump cold side linked with the fan-coils

The system consists of 6 main components:

8- Evaporator
9- Water storage
10-Pump
11-Valve
12-Fan-coil
13-Pump

The evaporator (8) performs the supplying of cold water. The water storage (9) enables the cold water to be available for the fan-coil device. The pump (10) performs the circulation of water in the fan-coil, while the valve (11) performs the regulation of flow.

The fan-coils (12) release colder air in the IT rooms to cool it. They function on the following principle: the cold water circulates in pipes, the fan-coils blow air on it and thus it gets cooled, and then the air is sent inside the IT rooms. The Pump (13) sends water heated on fan-coil evaporator.

The maximal installed effect of cooing a fan-coil is 200KW. However, only 63kW were installed for the fan-coil, as it is shown in Figure 9, because it was a current cooling need of the building in the IT rooms. In the case of building extension and residents' requirements, there is a possibility to install a new fan-coil for the IT room cooling. Because of this low cooling load, the provided condenser heat to support the main heating branch was also low and with low temperature.

It means that the maximal cooling load of the fan-coil is 63kW, and the maximal installed cooling effect is 200KW, which keeps a reserve for putting more computer equipment in the room. Water storage is very important, because even if the fan-coil power is almost constant, the heat pump does not work all the time and thus limits the operation time. The heat pump starts working again when the water temperature in a storage exceeds a certain temperature.

The significance of the two pumps (10 and 13) is also very important, they perform the regulation of flow from both sides of water storage, following the needs for cooling the IT rooms.

4. METHODS AND CALCULATION

4.1. Defining of condenser temperature (Tcond)

The figure presents the outdoor temperature in Trondheim for the year 2011.

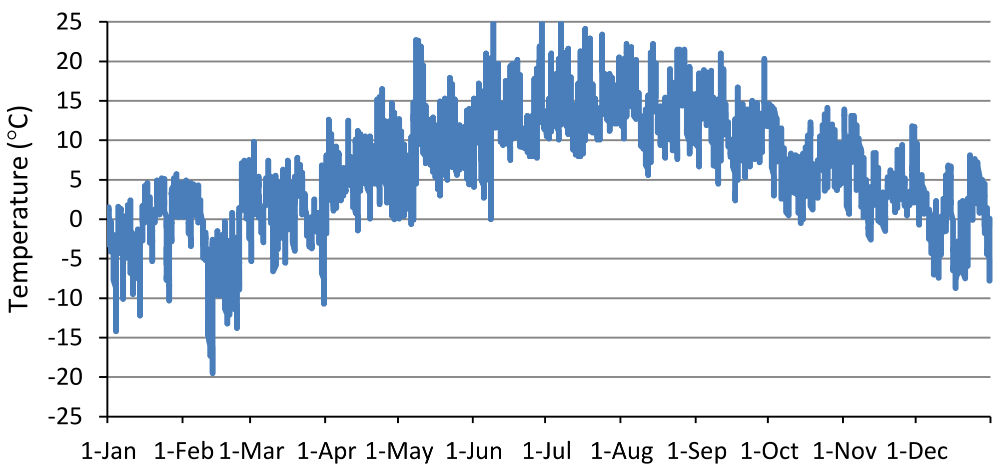


Figure 10. Outdoor temperature in Trondheim in 2011

To obtain the condenser temperature (Tcond) from the outdoor temperature (Tout), we will use the curve given in the ”Office case study, Source book” to obtain the temperature of the main heating branch water supply (Tsup). Figure 11 presents the experimental curve Tsup which is if the function of outdoor temperature.

$$Tsup = f(Tout)$$

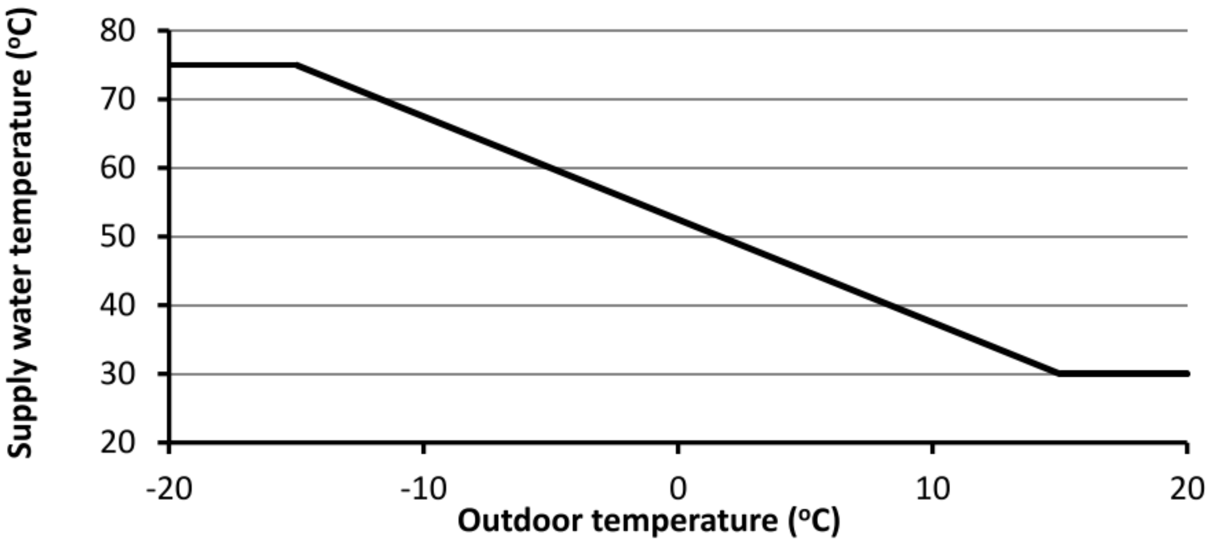


Figure11: Outdoor temperature compensation curve of the main heating branch

The condenser temperature is directly related to the return temperature of water from the main heating branch (Tret):

$$Tret = Tsup - \Delta T1$$

A greater ΔT1 temperature is more adequate for heating system operation and, relying on the book [14] we that the temperature is constant and that it is 20°C.

$$Tcond = Tret + \Delta T2$$

In this case, ΔT2 is constant and it is 5 °C.

4.2. Defining of Qcond and Pcomp

The basic goals are the estimation of the condenser load (Qcond) and the estimation of the compressor power by means of the cooling load (Qev) and condenser temperature (Tcond).

The purpose of this step is to find the curve equation so that we can obtain much higher values for the condenser load (Qcond) and compressor power (Pcomp) in the function of the condenser temperature (Tcond) and cooling load (Qev).

The curve equation is defined by simulation in CoolPack for:

$$Q_{ev} \epsilon \{0,40,60,80..\} \text{ and}$$

$$T_{cond} \epsilon \{5,15,25,35,..\}$$

Pursuant to a SINTEF document, the Qev cannot go beyond 200kWh, because that value has been defined during the construction and making. That is why even when Qev was greater than this limitation in our calculation, it has been considered to be 200kWh.

The simulation in CoolPack has been performed with the assumptions of some hypotheses:

- ΔT_{SH}=2K
- ΔT_{SC}=2K
- Cooling fluid freon R-410a, which belongs to the group of HFC gases has been used,
- Te=8°C

To get a movement line equation for this graph, thy have been considered as 6^{th}-degree polynomials. The determination coefficient R2 is obtained to be 1 for all the curves, so that the trend line equations for all equations are reliable and can be used.

Thanks to CoolPack and the data from “Office Building Case Book” the values are obtained for

$$Pcomp = f(Tcond, Qev)$$

$$Qcond = f(Tcond, Qev)$$

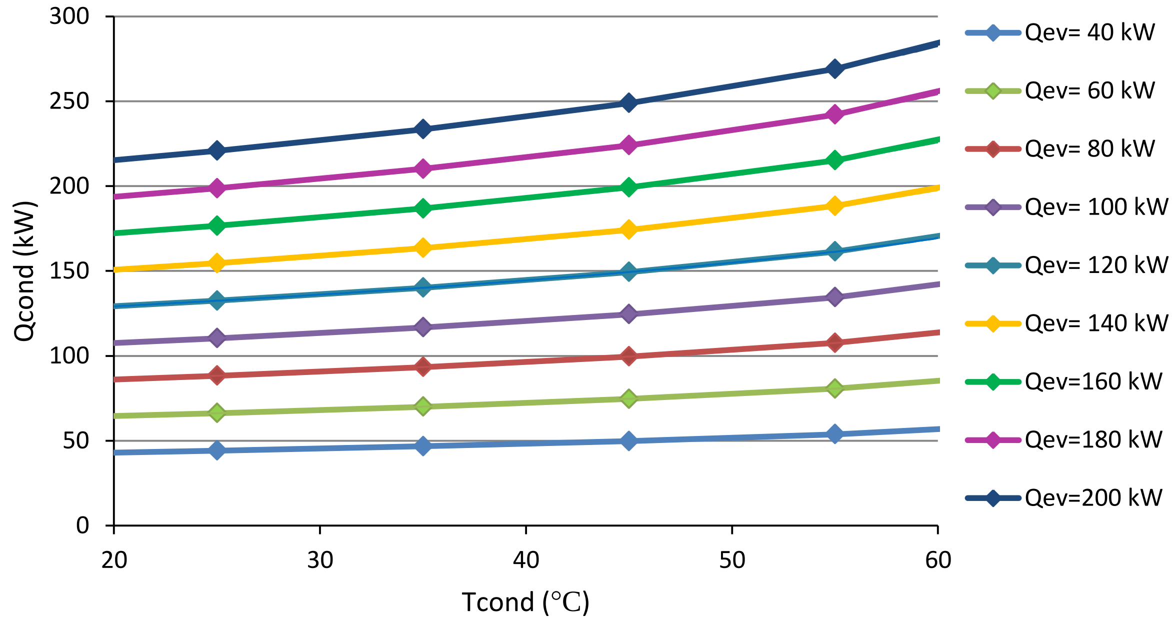


Figure 12: Qcond=f(Tcond, Qev) found with Cool Pack and SINTEF document

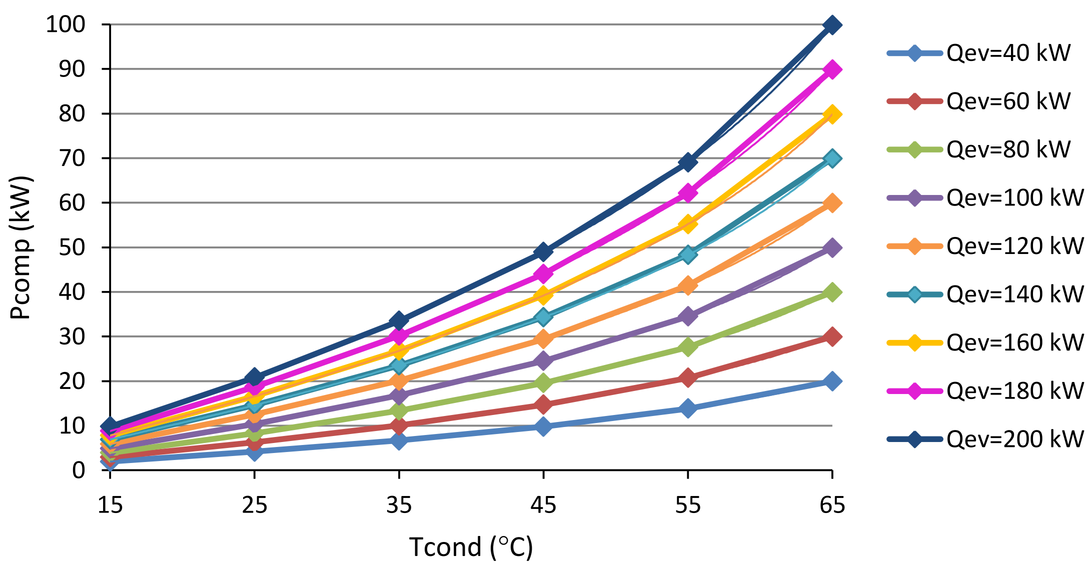


Figure 13: Pcomp=f(Tcond,Qev) found with Cool Pack and SINTEF document

4.3. Energy use

From the diagram (Figure 14) we can see that the condenser load increases with the increase of evaporator loaf and that the greatest calculated values are found in the winter period.

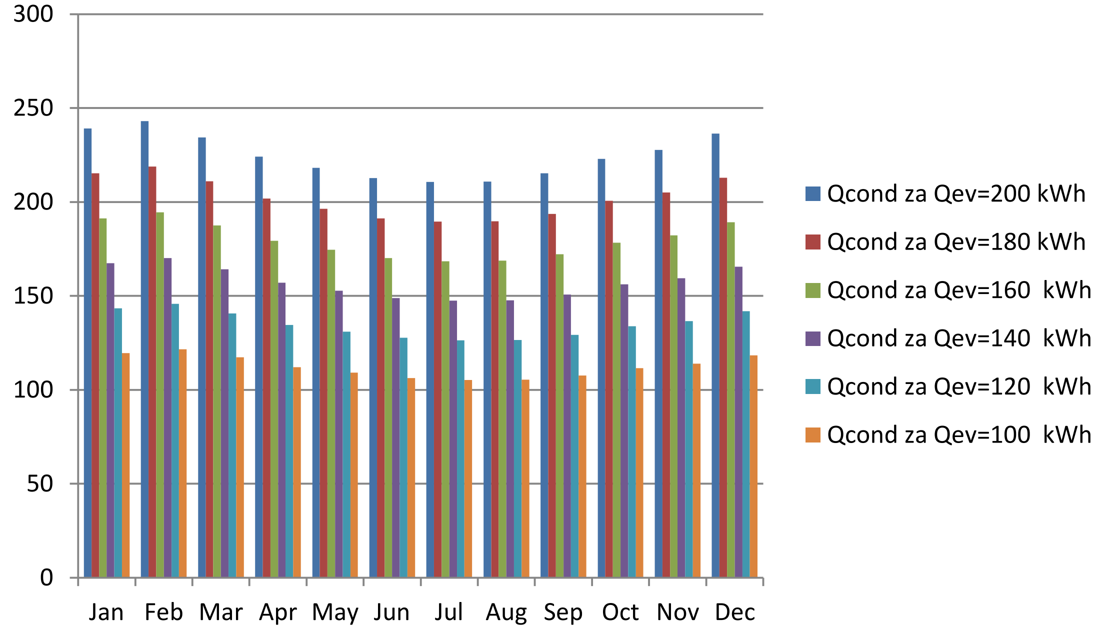


Figure 14: Monthly values of the condenser load (Qcond) for different values of the evaporator load (Qev)

From the diagram (Figure 15) it can be seen that the compressor power increases with the increase of the evaporator load and that the highest values are calculated in winter period, same as in the previous diagram.

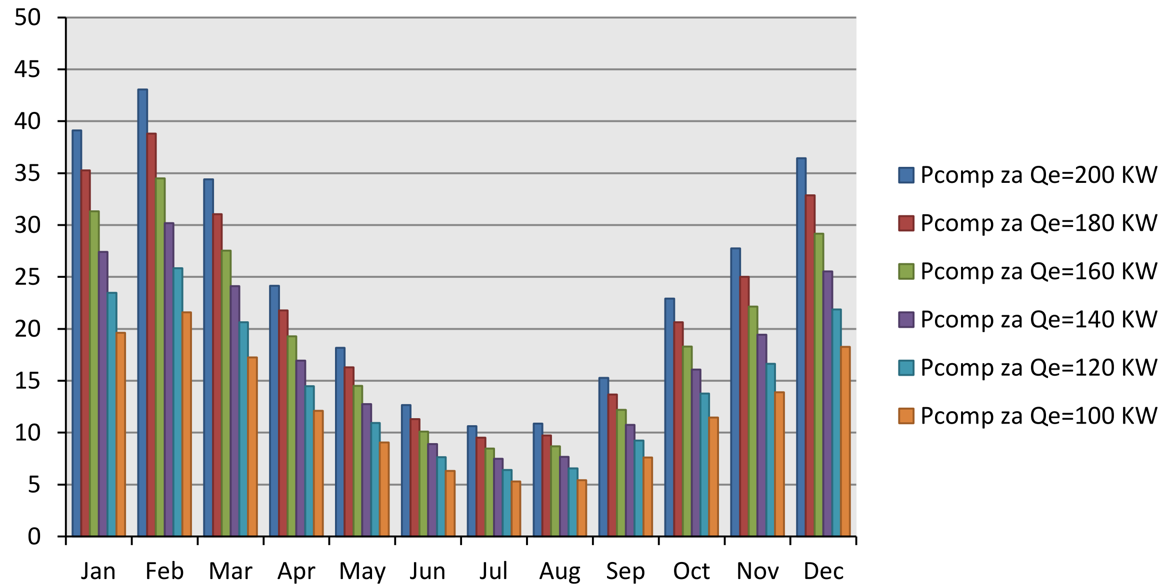


Figure 15: Monthly values of the compressor power (Pcomp) for different values of the evaporator load (Qev)

For further calculation, we will assume that the evaporator load is constant and that it is Qev=200 KW.

On the basis of the assumption that the evaporator load is constant and that it is Qev=200 KW, we will obtain the monthly values for Qcond and Pcomp as it is shown on the following diagrams (Figures 16 and 17).

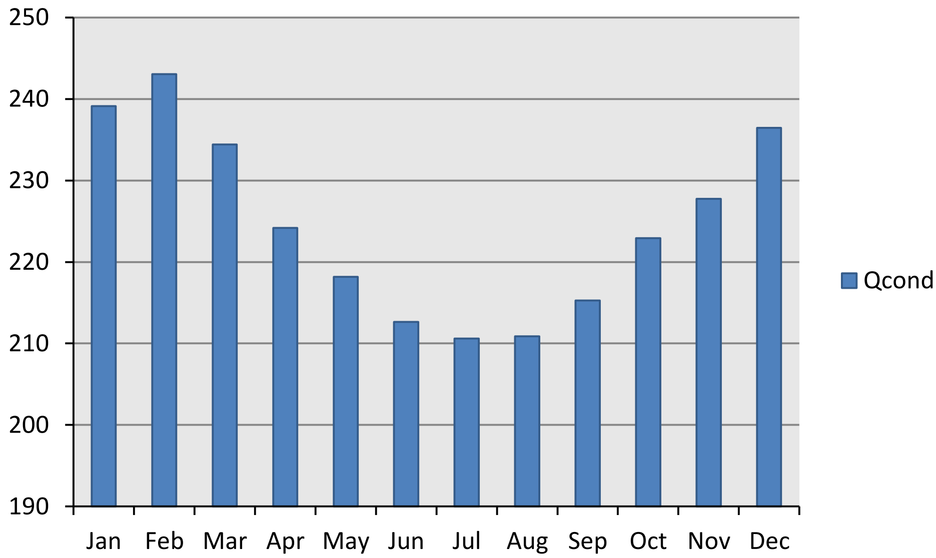


Figure 16: Heat production at the condenser

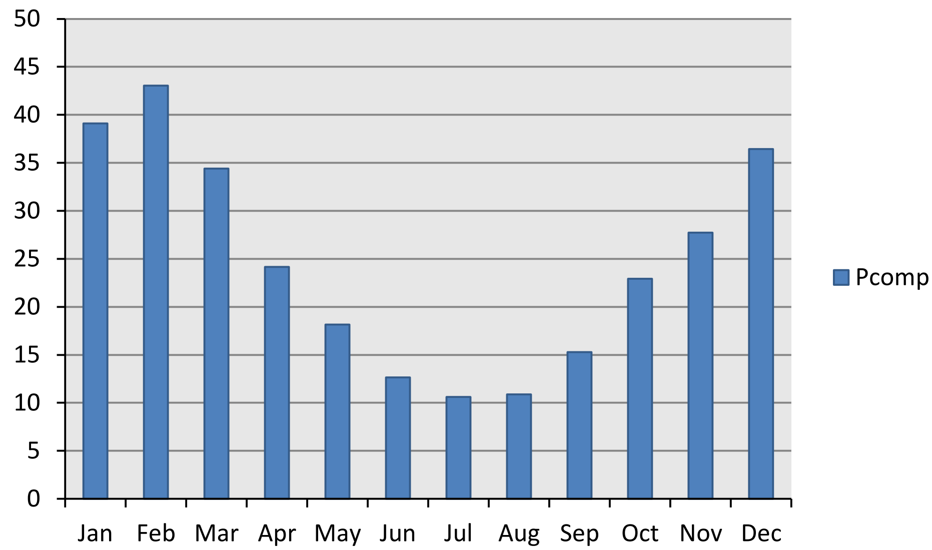
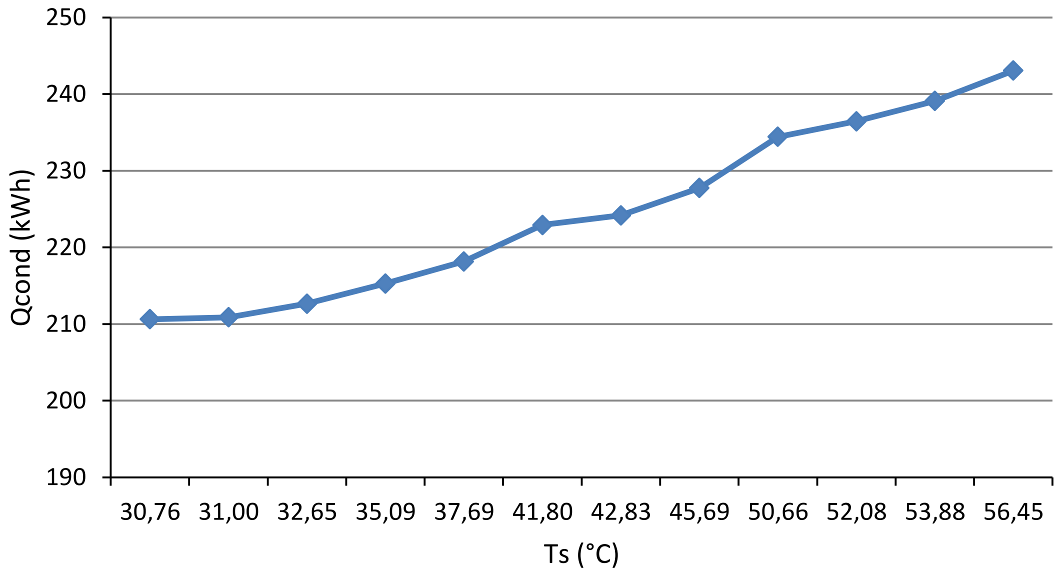


Figure 17: Compressor electricity use

If we observe the change in the condenser load (Qcond) depending on the supply temperature (Ts) and condenser temperature (Tcond), we can notice that with the increase of the supply temperature (Ts), the condenser load (Qcond) is also increased (Qcond), what can be seen in the following diagrams (Figure 18).



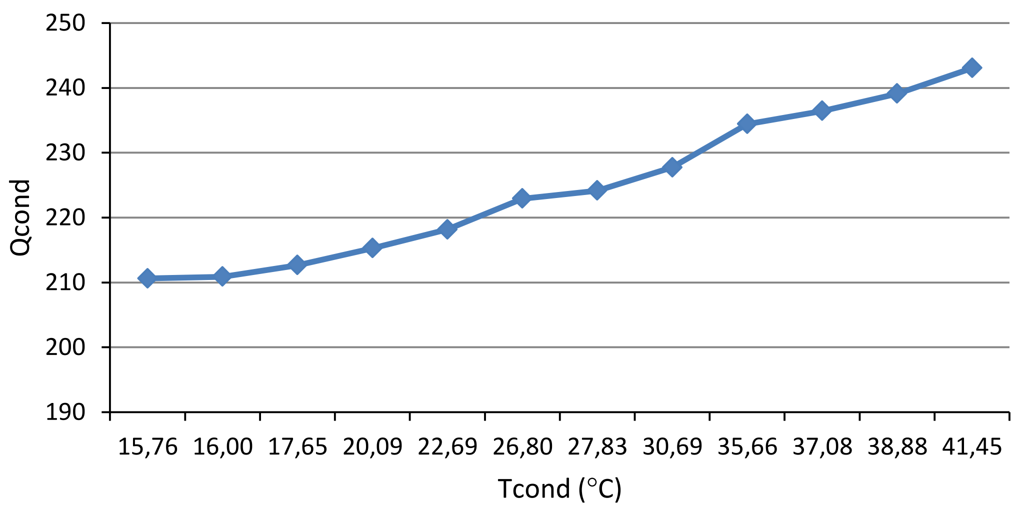


Figure 18: Condenser load (Qcond) change depending on the temperature (Tcond) and supply temperature (Ts)

5. SYSTEM PERFORMANCE

The most important characteristic of a heat pump is the relation between the obtained and used energy which also defines the economy of a device. This characteristic is known as the Coefficient of Performance (COP). For a heat pump to be more efficient, we should strive for a greater coefficient of performance, which, speaking theoretically, cannot be smaller than the number one.

5.1. Coefficient of performance (COP)

The efficiency of a heat pump is defined by means of the coefficient of performance (COP).

Due to these formulas, it is possible to find the connection between the COP and temperature.

$$COP = \frac{Energy\ transferes\ by\ the\ heat\ pump}{Power\ consumed}$$

It means that

$$COP = \frac{Q_{ev}}{W}$$

Compressor power W (Pcomp) is calculated by means of the formula:

$$W = Q_{cond} - Q_{ev}$$

If we include that in the formula for calculating the heat pump coefficient of performance, we get:

$$COP = \frac{Q_{ev}}{Q_{cond} - Q_{ev}}$$

That is:

$$COP = \frac{Q_{cold}}{Q_{hot} - Q_{cold}}$$

Finally, we obtain the connection between the COP and temperature:

$$COP = \frac{T_{cold}}{T_{hot} - T_{cold}}$$

$$COP = \frac{T_{ev}}{T_{cond} - T_{ev}}$$

In the following diagrams, the influence of outdoor temperature (Tout) and condensation temperature (Tcond) to the heat pump efficiency is shown.

The diagram that follows presents the change in the coefficient of performance (COP) in relation to the condenser temperature (Tcond). From the diagram, we can see that if the condenser temperature decreases, the coefficient of performance (COP) increases.

In the following diagrams we can see the influence of outdoor temperature and condensation temperature to the heat pump efficiency (Figures 19 and 20).

The coefficient R^2 = 0,9921 implies that the outdoor temperature has a great influence to the heat pump efficiency and that with the increase of outdoor temperature the heat pump efficiency gets increased too.

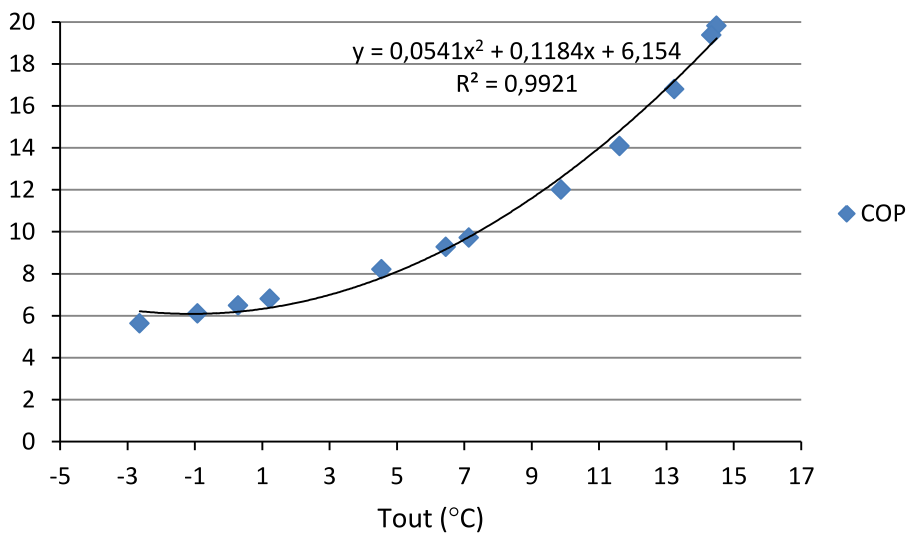


Figure 19: Influence of outdoor temperature to the heat pump efficiency

As a difference from the previous diagram, this diagram (Figure 18) shows that the heat pump efficiency is decreased with the increase of condensation temperature (Tcond).

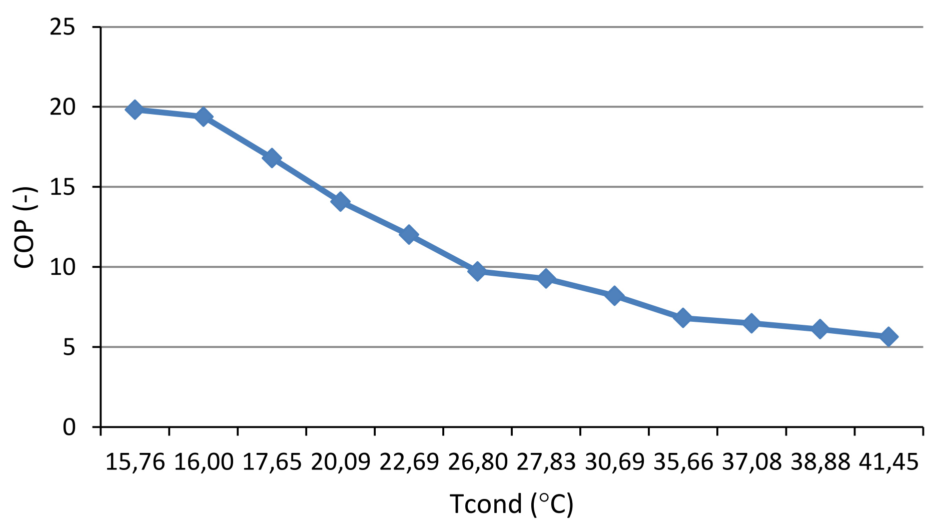


Figure 20: The influence of condensation temperature to the heat pump efficiency

The diagram (Figure 21) presents the average monthly values for the coefficient of performances (COP) for heating, and from there we can see that the values of this coefficient are higher in summer months. We also see that for the assumed conditions high values of the coefficient of performances have been obtained, in the interval from 5.64 to 19.82, and that is not so usual.

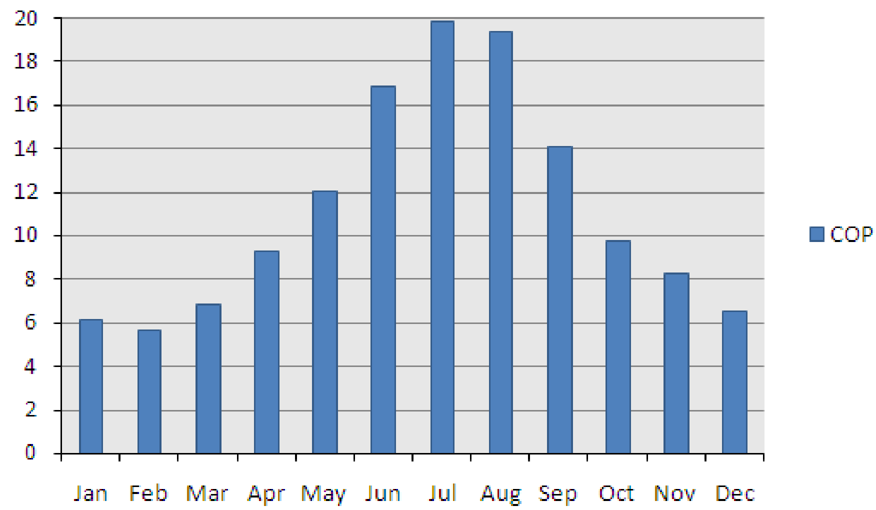


Figure 21: Average monthly values for the COP for heating

The change in the the evaporator load (Qev) also influences the system performances, what can be seen in the following diagram (Figure 22).

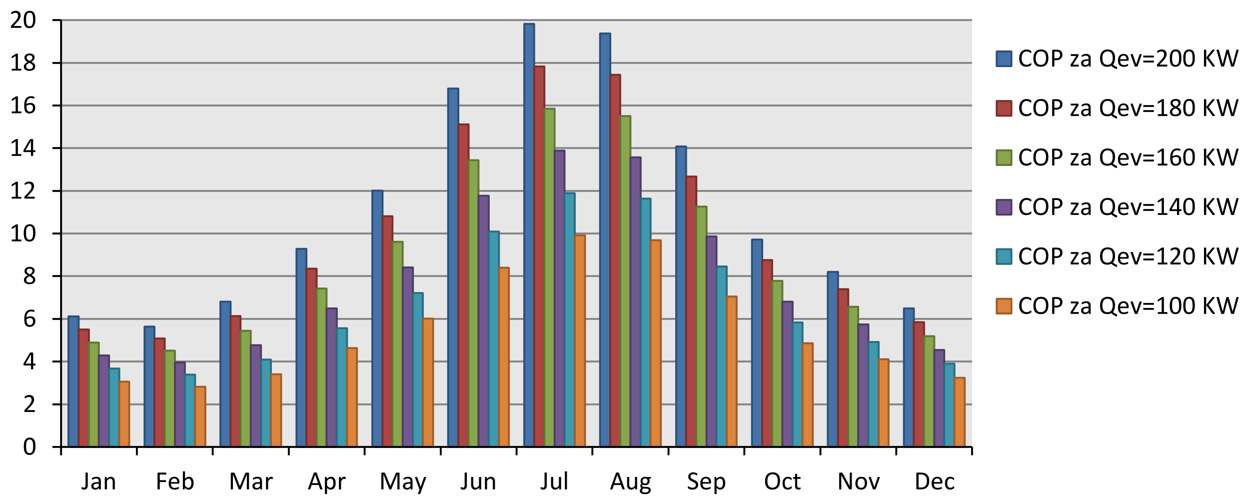


Figure 22: Monthly values of the coefficient of performances (COP) for different values of the evaporator load (Qev)

It can be seen from the diagram that with the decrease od the evaporator load, the heat pump coefficient of performances also decreases.

6. COST-BENEFIT ANALYSIS

To estimate the energy savings for different prices of electricity and district heating, we have erformed a Cost-benefit analysis.
In the analyzed case study thr energy savings have been calculated as:

$$Energy\ saving = Q_{cond} \cdot C_{DH} + P_{comp} \cdot C_{EL}$$

where Cel and Cdh are the prices of electricity and district heating.
Pcomp [kWh] and Qcond [kWh] are the compressor consumption and heating energy provided by the condenser.

In 2011 the price of electricity was about 1 NOK/kWh (1 EUR = 7.83 Norwegian krone (NOK)) (Statistics Norway, 2011). Depending on energy producers in different towns, the price of district heating was about 0.5 - 0.95 NOK/kWh.

We have observed four cases:

1. energy saving has been calculated by assuming that the price of district heating is C_{DH}=0,75 NOK/kWh, and that the price of electricity is C_{EL}=1 NOK/kWh

$$S_1 = Q_{cond} \cdot 0.75 + P_{comp} \cdot 1$$

2. C_{DH}=0,55 NOK/kWh
   C_{EL}=1 NOK/kWh

$$S_2 = Q_{cond} \cdot 0.55 + P_{comp} \cdot 1$$

3. C_{DH}=0.65 NOK/kWh
   C_{EL}=1 NOK/kWh

$$S_3 = Q_{cond} \cdot 0.65 + P_{comp} \cdot 1$$

4. C_{DH}=0,75 NOK/kWh

$$S_4 = Q_{cond} \cdot 0.75$$

Now we will observe the differences in results obtained for different parameters (prices). The result of the Cost-benefit analysis are given in the following diagrams.

The diagram (Figure 23) presents the energy saving values at the annual level for all four cases. From the diagram, it can be seen that the biggest saving is for the case 4, i.e. that the case 4 presents the best variant, while the case 2 is the worst.

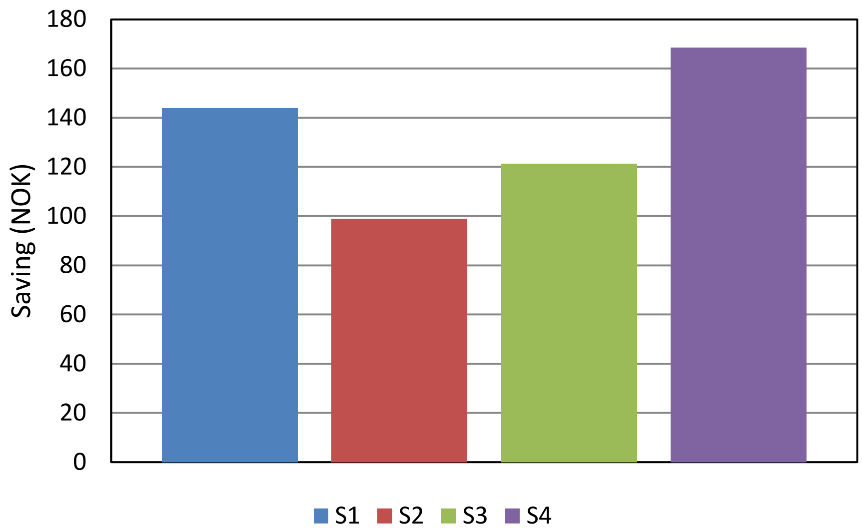


Figure 23: Annual energy savings

6.1. Sensitivity of energy savings

The diagram (Figure 24) presents the monthly energy savings depending on outdoor temperature. (Tout). From the diagram, it can be seen that there is an evident dependance between th saving and outdoor temperature. For the first case, the degree of saving increases with the decrease of temperature, while the situation is not the same for the other three ones. In S_2, S_3 and S_4, the degree of saving increased with the increase of temperature.

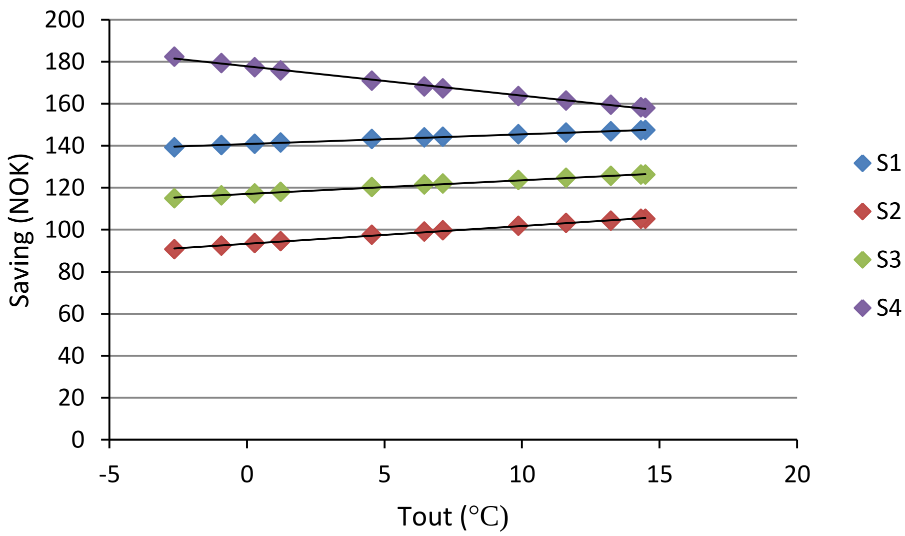


Figure 24: Monthly energy savings depending on Tout

The diagram (Figure 25) presents the monthly energy savings depending on supply temperature (Ts).

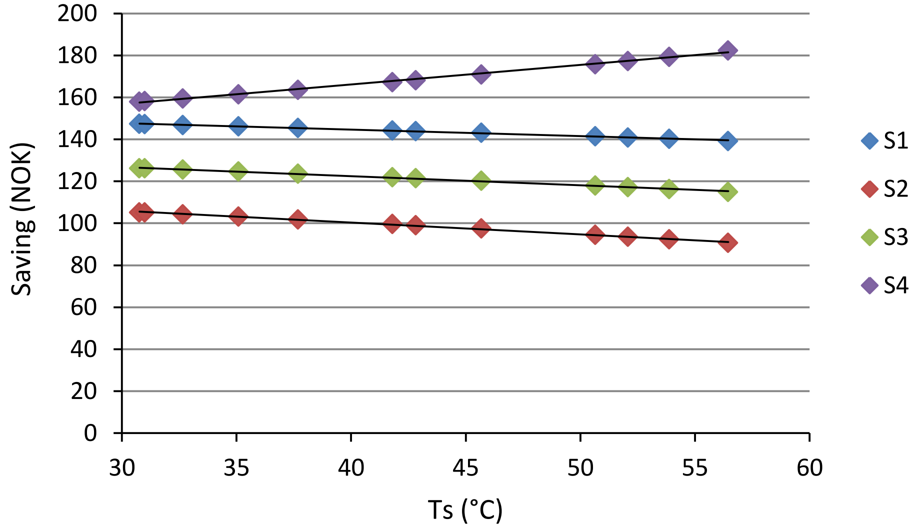


Figure 25: Monthly energy savings depending on Ts

Finally, the diagram (Figure 26) presents the monthly energy savings for all four cases, i.e. for different energy prices.

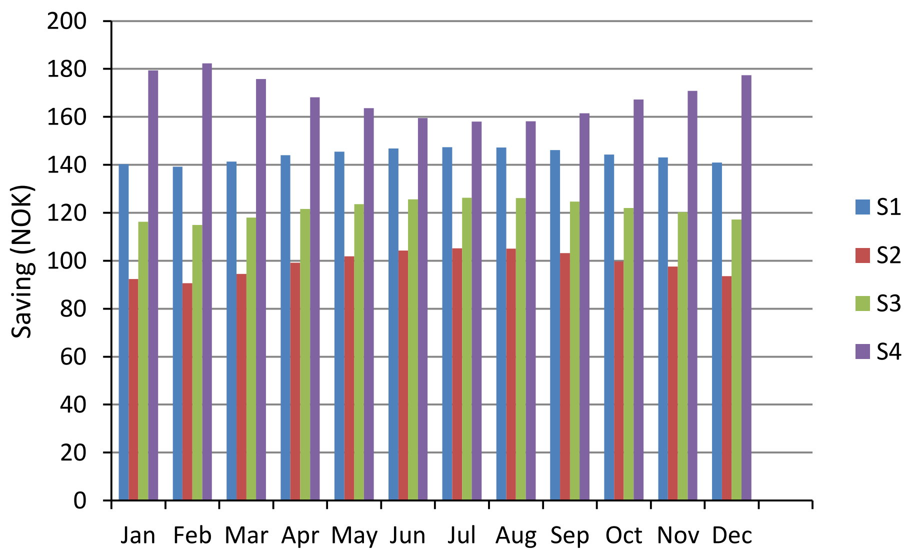


Figure 26: Monthly energy savings for different energy prices

7. SENSITIVITY ANALYSIS OF THE ENERGY SAVINGS INCLUDING DIFFERENT OPERATION PARAMETERS

7.1. The influence of the evaporator temperature (Te) to energy savings

We will change the hypothesis on the evaporator temperature and assume that the evaporator temperature is Te=6°C. In the same way we will do the simulation in CoolPack, for the same conditions and the evaporator load Qev=200KWh.

In the following diagram (Figure 27), we can see that the condenser load increased with the decrease of the evaporator temperature.

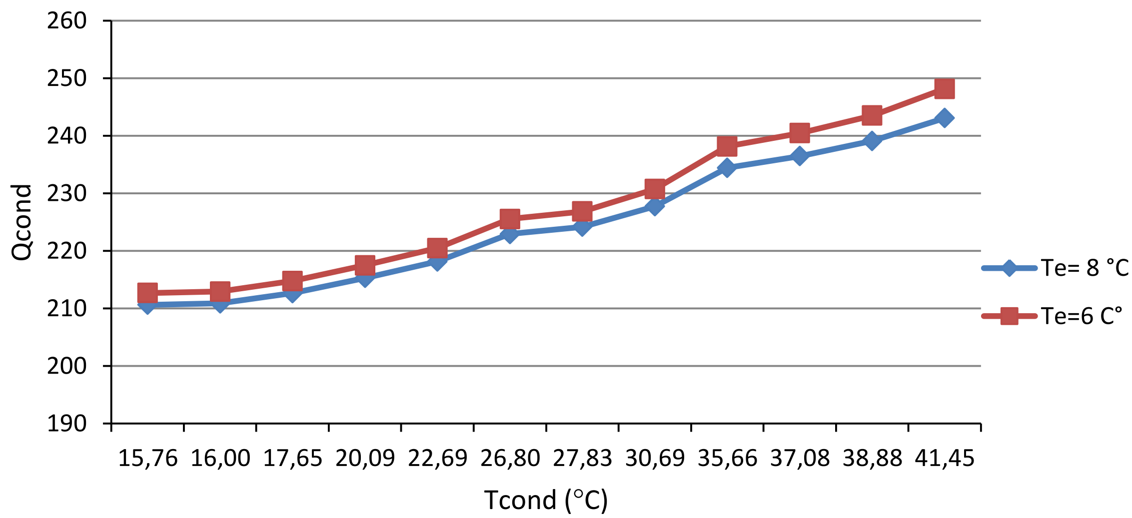


Figure 27: The condenser load change depending on Te and Tcond

With the change of the condenser load, the coefficient of performances also changes. In the diagram (Figure 28) we can see the average monthly values of the COP for different evaporator temperatures.

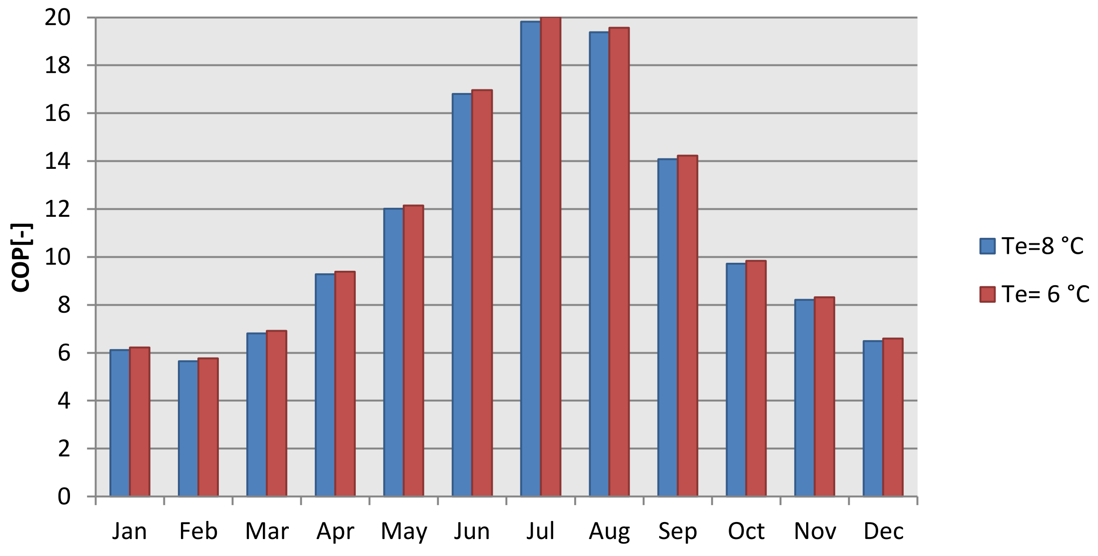


Figure 28: Average monthly values of the COP depending on Te

Finally, the evaporator temperature affects the energy savings, what can be seen in the following diagram (Figure 29).

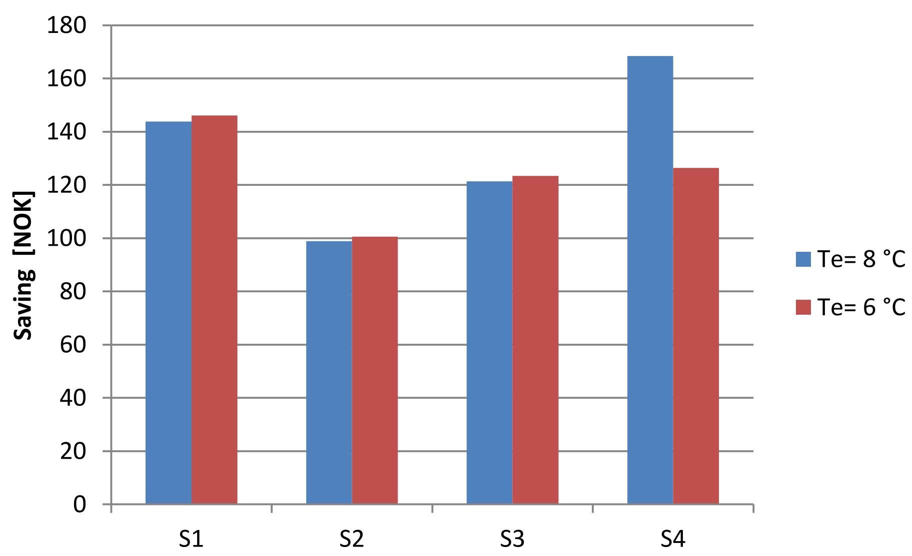


Figure 29: Average energy savings for different values of Te

It can be seen from the diagram that the energy savings change (increase) with the decrease of temperature, except for the case S4, when $S_4 = Q_{cond} \cdot 0.75$, i.e. when the influence of the compressor power has not been taken into consideration, we can say that in that case, at the evaporator temperature decrease, the savings also decreased

7.2. The influence of refrigerant to energy savings

Instead of the R410A refrigerant, we will choose the R407C refrigerant.

After many years of testing and investigation, R407C is recognized as a suitable alternative refrigerant for R22 in medium and high temperature applications such as residential and light commercial air conditioning. R407C is a ternary blend of hydro fluorocarbon or HFC compounds, comprising 23% of R32, 25% of R125 and 52% of R134a. It has no chlorine content, no ozone depletion potential, and only a modest direct global warming potential. ODP = 0, GWP = 1610.

In the diagram (Figure 30) the change of the condenser load (Qcond) depending on temperature (Ts) has been shown.

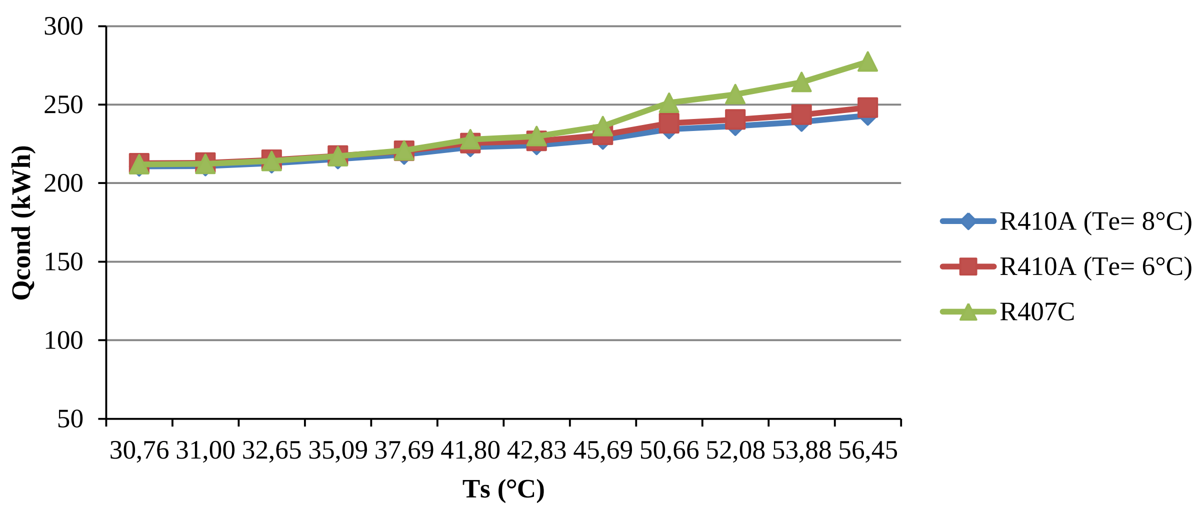


Figure 30: The change of Qcond depending on Ts for different refrigerants

It can be seen from the diagram that the change of refrigerant has the biggest influence to the calculation by now, for the mentioned refrigerant we obtain bigger condenser load, what can be seen in the following diagram (Figure 31).

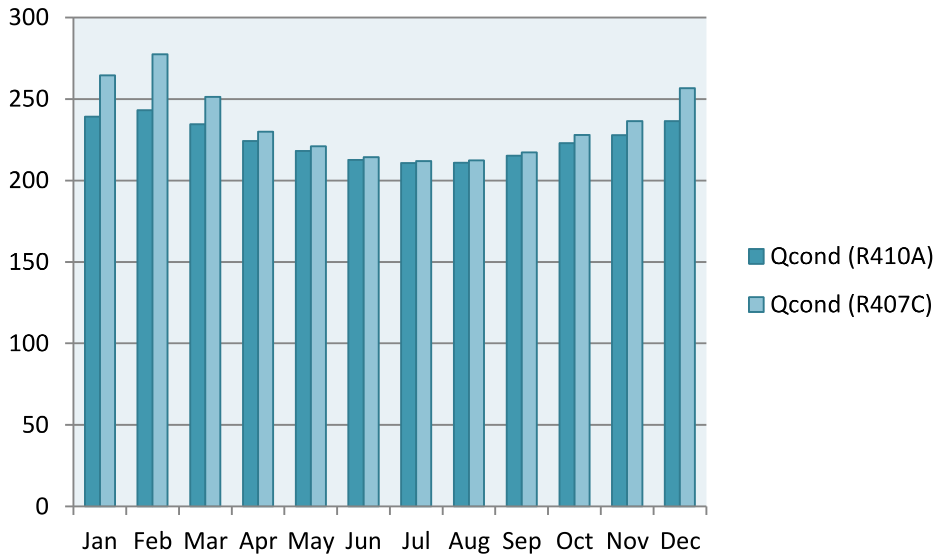


Figure 31: The change of Qcond for different refrigerants

The diagram (Figure 32) presents the comparative values for two different refrigerants, at the same environmental temperature, condensation temperature and at the same evaporator temperature, as well as at the condenser load Qcond= 200 KWH.

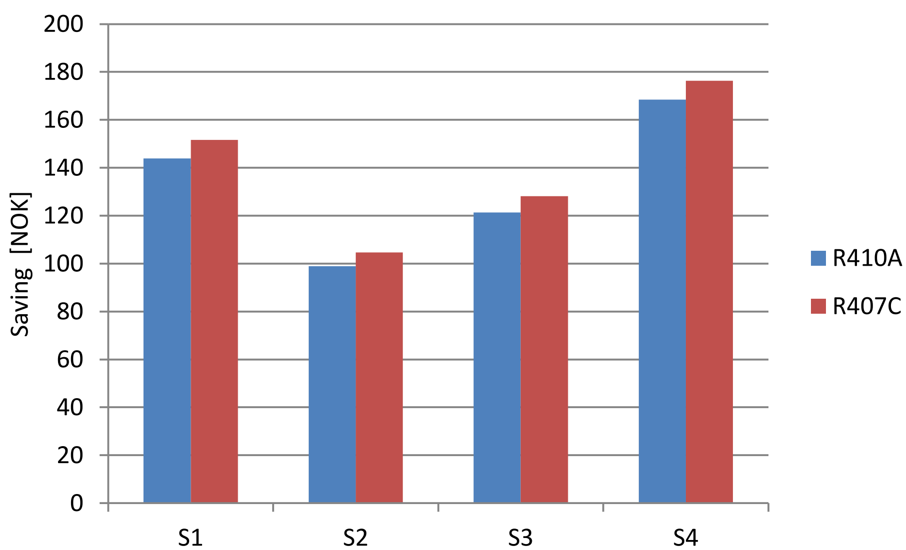


Figure 32: Average energy savings for refrigerants

We could see from the analysis that in both cases (at the change of evaporator temperature and at the change of refrigerant) we have had greater savings of energy and money.

8. DISCUSSION

We will a Cost-benefit analysis for the same case building, but for the prices of electricity and district heating for the area of Bosnia and Herzegovina.

Energy savings in the analysed case study were calculated as:

$$Energy\ saving = Q_{cond} \cdot C_{DH} - P_{comp} \cdot C_{EL}$$

The price of electricity for Bosnia and Herzegovina goes from 0.15 to 0.18 BAM/kWh (1 BAM = 1.95 EUR), and the price of district heating goes from 0.10 to 0.15 BAM/kWh.

1. energy savings have been calculates by assuming the district heating price is C_{DH}=0,15 BAM/kWh, and that the electricity price is C_{EL}=0.10 BAM/kWh

$$S_1 = Q_{cond} \cdot 0.10 - P_{comp} \cdot 0.15$$

2. C_{DH}=0,55 BAM/kWh
   C_{EL}=1 BAM/kWh

$$S_2 = Q_{cond} \cdot 0.17 - P_{comp} \cdot 0.13$$

3. C_{DH}=0.65 BAM/kWh
   C_{EL}=1 BAM/kWh

$$S_3 = Q_{cond} \cdot 0.15 - P_{comp} \cdot 0.18$$

4. C_{DH}=0,75 BAM/kWh

$$S_4 = Q_{cond} \cdot 0.17$$

The results of the Cost-benefit analysis for the area of Bosnia and Herzegovina are given in the following diagrams.

The diagram (Figure 27) presents the values of energy savings on annual level for all four cases. It can be seen from the diagram that the savings are the biggest for the case 4, i.e. that the variant 4 presents the best one, while the case 1 presents the worst variant.

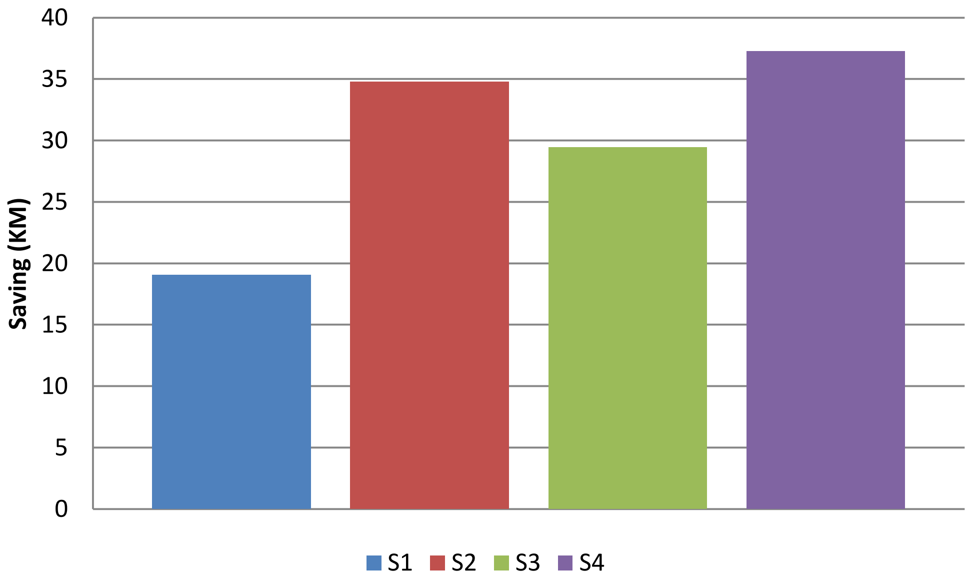


Figure 33: Annual of energy saving in Bosnia and Herzegovina

8.1. Sensitivity of energy savings

The diagram (Figure 28) presents the monthly energy savings depending on outdoor temperature (Tout). The values of average outdoor temperature for Bosnia and Herzegovina have been given for the period from 2010 to 2012.

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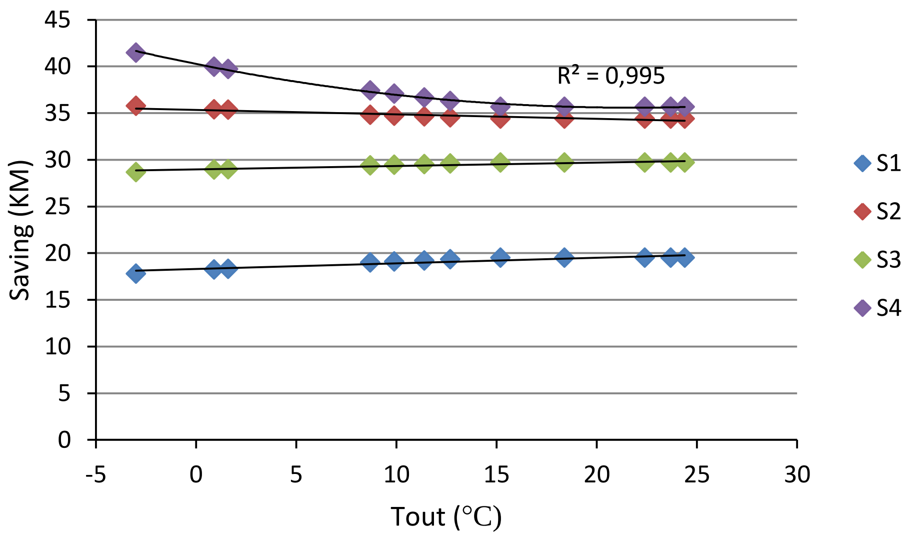

Figure 34: Monthly energy savings depending on the Tout in Bosnia and Herzegovina

It can be seen from the diagram that the change of monthly energy savings in relation to the outdoor temperature for the case S4 is not linear, but it corresponds to the second degree polynomial R^2=0,995, and that was not the case for Norway.

In the diagram (Figure 29), the monthly energy savings in Bosnia and Herzegovina depending on the supply temperature (Ts) is shown.

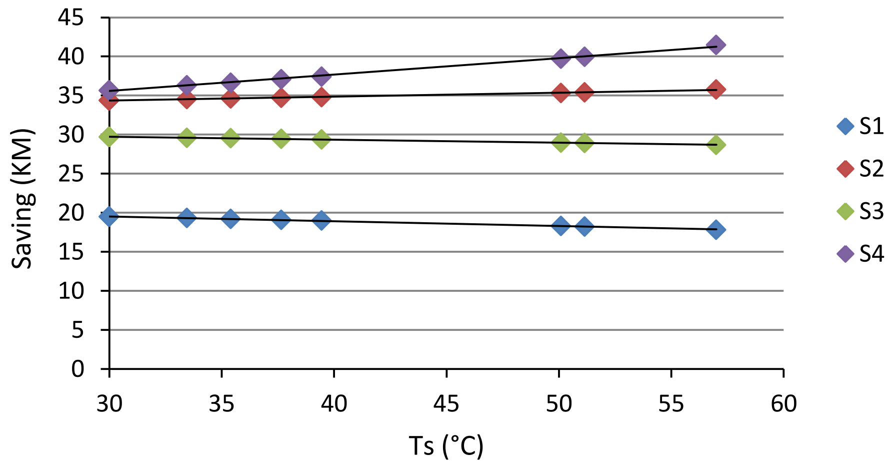

Figure 35: Monthly energy savings depending on the Ts in Bosnia and Herzegovina

In the following diagram, (Figure 30), monthly energy savings for all four cases are presented.

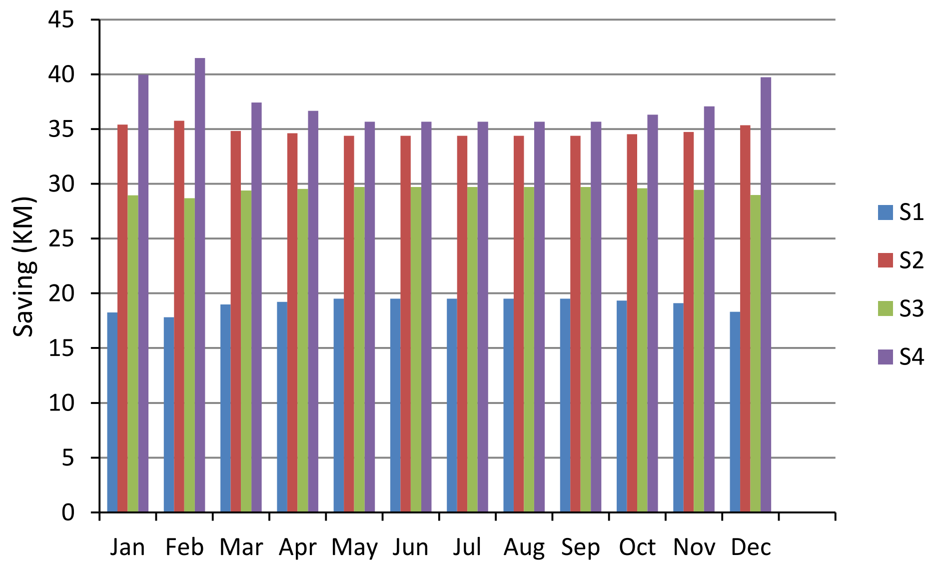

Figure 36: Monthly energy savings for different energy prices in Bosnia and Herzegovina

It can be seen from the diagram that the greatest savings were realized in December, January and February, same as in Norway.

9. CONCLUSION

The topic of this paper has been the Utilization and estimation of waste heat in buildings by using heat pump. Through the analysis, it has been shown on a concrete example that the use of heat pump not only has a positive influence to the environment, but it also carries great savings, not only in energy but also in money.

After the presentation of a low-energy building, an analysis of its substation has been performed, together with a detailed description of the heat pump.

By means of CoolPack and the SINTEF document, basic units of the heat pump have been calculates and the analysis of energy use has been performed.

A techno-economic analysis has been performed in this paper. It has been done to estimate the saved energy and money, i.e. to increase the savings. The influence of different parameters to the change of energy savings has been performed, and at the end a Cost-benefit analysis for Bosnia and Herzegovina has been performed.

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